A

Synopsis on

"THERMODYNAMIC PERFORMANCE EVALUATION OF DOMESTIC HYBRID SOLAR DRYER"

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1. Introduction

The increasing global population has increased the total consumption of food and raised a question of food security to the entire humanity. The possible solution to this is to produce more that is being done (Singh et al., 2018) and to reduce the demand of the food by controlling or reducing the global population (Satpute, 2016). In this sequence, reducing post-harvest losses and improving food storage and preservation techniques seems an alternative. The post-harvest losses of about 40% were reported for perishable items (El-Sebaii and Shalaby, 2012). The moisture removal (i.e. drying) from a food item is one of the most important preservation techniques practiced traditionally for a very long time. Drying is an energy-intensive process as it involves both heat and mass transfer phenomena. It can be performed as open-air sun drying, firewood/ fuel drying, electrical drying, and solar drying (Tiwari et al., 2016). Several factors are there that should be considered before selecting any drying process as every method has its advantages and drawbacks. Rahman (2006) suggested three main factors for the selection of a drying process. (i) The quality of products concerning the requirement. (ii) The economics of the process. (iii) Environmental impact on the process. The use of solar energy for drying applications can reduce the conventional energy requirements by 27% to 80% and, in this way, also contributes to international sustainability goals (Ahmad and Prakash, 2019).

A considerable amount of research has been done on the utilization of solar energy by using various solar dryers. Different designs of solar dryers are available in the literature. The general classification of the solar dryer can be done based on the mode and direction of air movement throughout the system, solar contributions, type of product to be dried, and insulation of the assembly (Kumar et al., 2016). Solar dryers are broadly classified in three categories, as shown in Figure 1.

In natural convection solar dryers, the solar-heated air circulates through the drying commodity due to buoyancy forces. These dryers are also called a passive type or free convection solar dryers. This type of dryer need no electric supply or any other power to work except solar radiation. It makes them more attractive to rural or remote areas where electricity is either not available or costs too high. The lower drying rate is one of the major limitations of this type of dryer (Ekechukwu and Norton, 1999).

Forced convection solar dryers, on the other hand, use an additional device such as a fan, pump or blower, *etc.* to circulate the solar-heated air through the drying commodities. These dryers are also known as active solar dryers. The drying rates were higher as compared to the natural convection solar dryers, but there is a need for electrical energy to drive the pump or blower. This makes the system more complex, dependent on conventional energy, and also increases the total cost of the system (Sukhatme and Nayak, 2018).

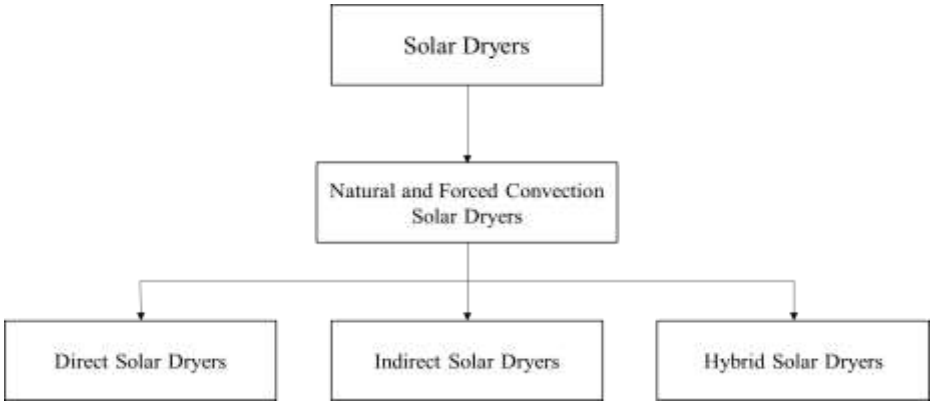

Figure 1 Classification of solar dryers (Kumar et al., 2016).

The natural and forced convection solar dryers can be further classified on the basis of mode of heat transfer to the drying commodity (El Hage et al., 2018).

In direct solar dryers, the product is placed over the drying tray inside a drying chamber having transparent walls or roofs. The solar radiations were allowed to strike on the product directly by passing through the transparent walls or roof. The solar radiation was directly absorbed by the product, which results in moisture evaporation. The process has its own drawbacks as there is direct contact between the solar radiation ad the product. Direct exposure to sunlight leads to discoloration and vitamin loss in the food items, which affects the quality (Singh et al., 2006). The direct type of dryers can be divided into cabinet type dryers and tunnel type dryers (Navale, 2016). A systematic arrangement of solar cabinet dryer and solar tunnel greenhouse dryer has been shown in Figure 2.

In indirect type of solar dryers, the drying commodity has no direct exposer to solar radiation. The product to be dried is placed in a well-insulated drying chamber. The drying air is heated separately using solar air heaters, and then this heated air is supplied to the drying chamber. The involvement of the solar air heaters makes the system more complicated as compared to direct

type, however the product quality obtained from indirect solar dryers was much better. Figure 3 shows a system of an indirect solar dryer.

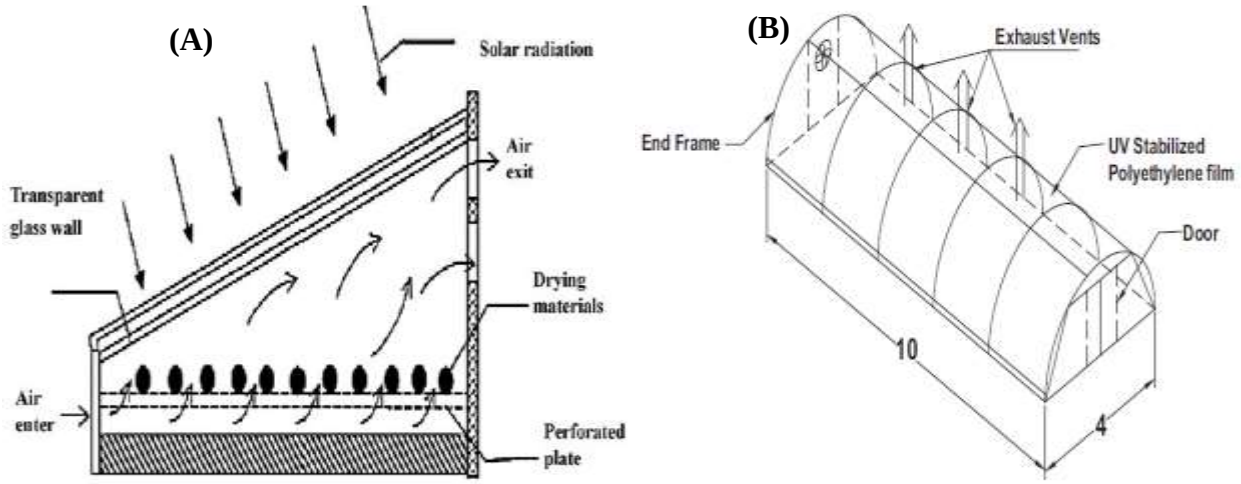

Figure 2 (A) Solar cabinet dryer (Sharma et al., 2009), (B) Solar tunnel greenhouse dryer (Arun et al., 2014).

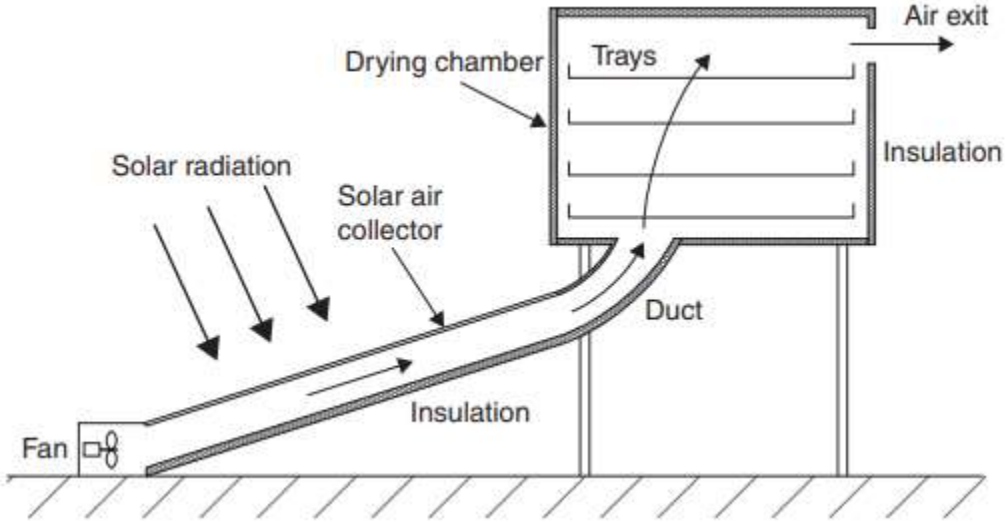

Figure 3 Indirect solar dryer (Kalogirou, 2014).

Hybrid solar dryers had an option to combine both the actions of solar air heating (direct and indirect solar air heating) and to use an auxiliary energy source for functioning. Hence, these dryers can be operated either only using solar energy, only using conventional energy sources, or using both. Generally, hybrid solar drying systems works with a range of 50–60% contribution of solar energy input (Belessiotis and Delyannis, 2011). Figure 4 shows the schematics of the hybrid solar dryer.

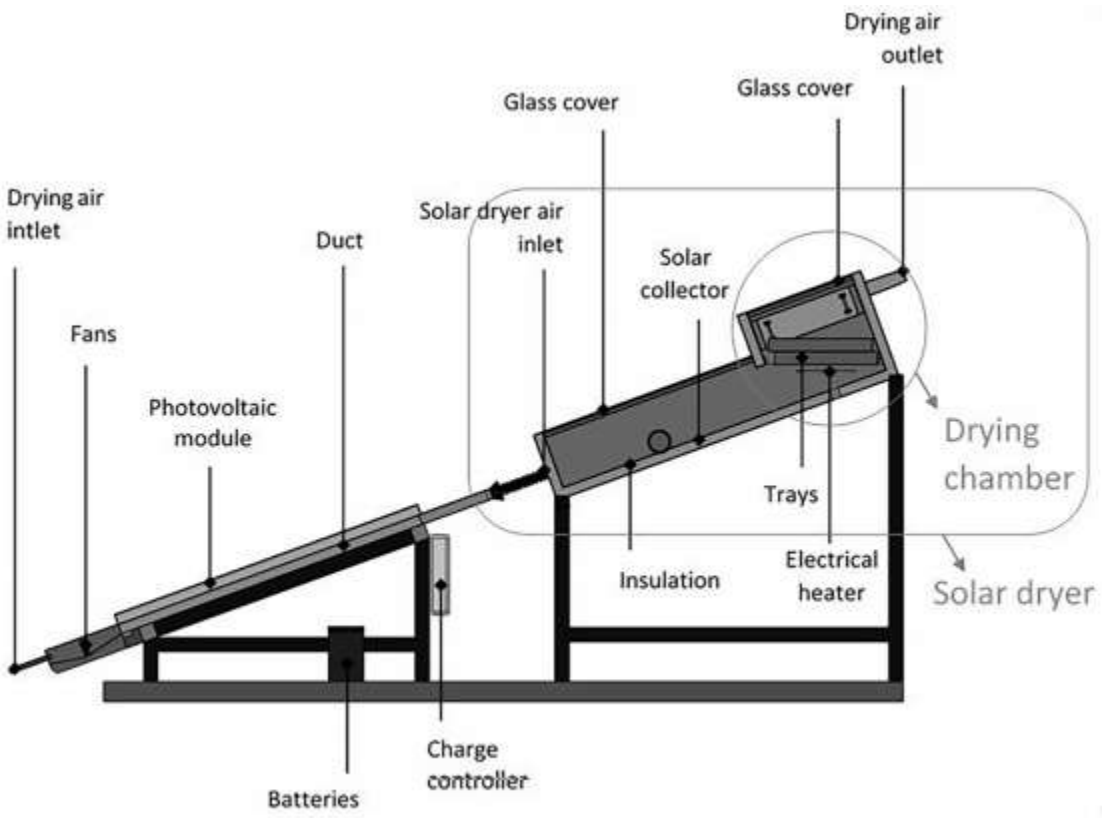

Figure 4 Schematics of the hybrid solar dryer (Silva et al., 2020).

Many agricultural products need to be dried at steady and moderate temperature conditions. Sometime, product needs drying for more than a single day to reach the required moisture content. The solar dryers are bound to work by using solar energy and during the period of off-shine, they just stop working. This is a massive drawback of solar technology and if the temperature inside the drying chamber during the sunshine hours becomes very high, that can either spoil the product to be dried or goes waste through the exhaust. So, to control the working temperature during the daytime and to maintain that after sunset, thermal energy storage systems can be used. They store the excess energy generated inside the drying chamber during the sunshine period and supply the same to the product during the off-sunshine period (Bal et al., 2010).

Thermal energy can be stored either in sensible and latent heats or in the form of chemical energy. Figure 5 shows the different classifications of thermal energy storage.

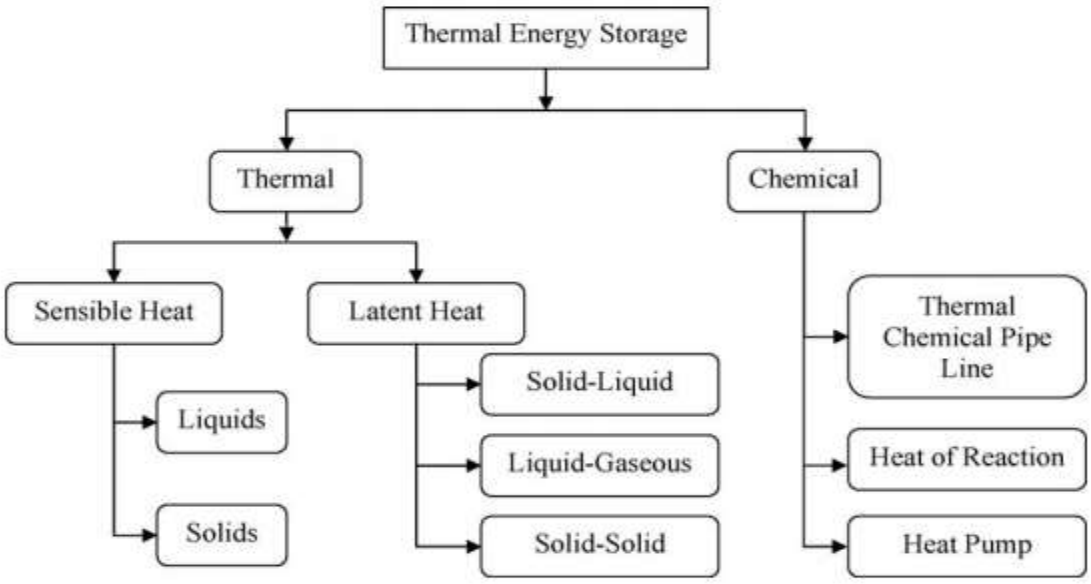

Figure 5 Classification of thermal energy storage (Bal et al., 2010).

As material changes from solid to liquid or liquid to solid, the emission of latent heat in the form of thermal energy occurs. The storage of latent heat was observed 5 - 14 times more heat per unit volume than sensible storage materials. The phase transition most studied for latent heat storage (LHS) is due to the low volumetric expansion. The phase transition between the solid and liquid states is more suitable compared to a liquid gas phase transition. The material undergoing the phase change in a latent heat storage system is commonly known as phase change material (PCM) (Nithyanandam et al., 2017).

A number of advantages have been observed in the case of the latent thermal storage in comparison to sensible thermal storage such as high heat capacity, less volume, low storage temperature, thermal energy storage, and release at an almost constant temperature. Therefore, LHS using PCMs attracted some researchers for thermal energy storage in solar drying applications (Ayyappan et al., 2015).

2. Literature review

Sharma et al., (1986) designed and developed a direct cabinet type solar dryer and tested for the drying of peas, grapes, and potatoes. The dryer efficiency was found to be 40%. They recommended the use of cabinet type solar dryer for rural and domestic areas.

Thanvi and Pande (1987) developed a direct type of low-cost solar dryer and tested for the drying of chili. The moisture content of the chilies was reduced from 86.3% to 4.1% (wb) in 9 days and 18 days in case of solar drying and open sun drying, respectively.

Sharma et al., (1990) compared the performance of a solar cabinet dryer and open sun drying for the drying of turnip, cauliflower, and green peas. The maximum temperature inside the drying chamber was found to be in the range of 80-85°C and 45-50°C for no-load and loaded conditions. The drying time was reduced by 4 hours, 12 hours, and 6 hours for the drying of turnip, cauliflower, and green peas, respectively. Figure 6 shows a sectional view of solar cabinet dryer.

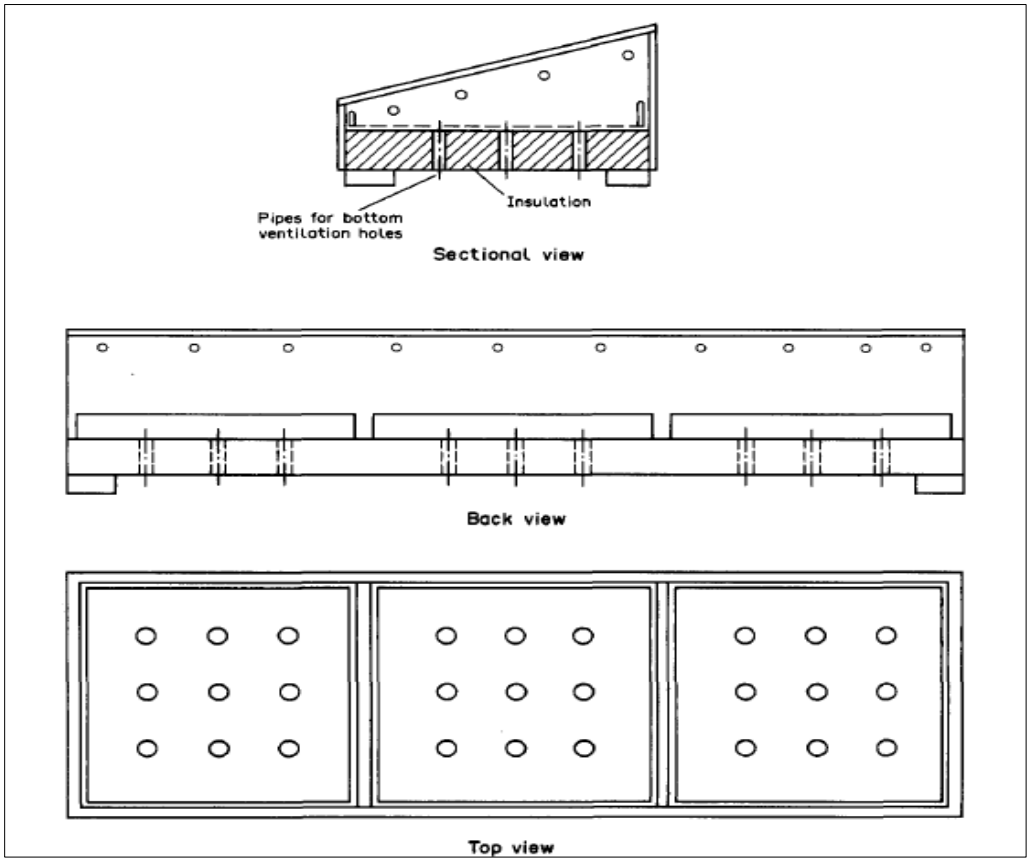

Figure 6 Sectional view of cabinet solar dryer (Sharma et al., 1990).

Mahapatra et al., (1994) used a direct solar dryer with an inside energy-absorbing surface for the drying of camomile from 75% (wb) to 7% (wb) of moisture content. By using FORTRAN 77 computer program was created for solving various equations and the predicting temperature, humidity, and moisture content.

Ampratwum and Dorvlo (1998) designed, developed and tested a direct type natural convection solar cabinet dryer under no-load conditions. The maximum value of the average temperature of the drying chamber and energy absorption rate was 84.82 °C and 0.93 kW/m^2, respectively.

Anwar and Tiwari (2001) analyzed the effect of collector length and mass flow rate of the hot air in a four-tray direct-cum-indirect type solar crop dryer. They reported that the evaporative heat transfer coefficient was more dominant than convective and radiative heat transfer coefficients. Its values increase significantly with an increase in collector length and mass flow rate of the hot air.

Basunia and Abe (2001) investigated a mixed mode natural convection solar dryer for rough rice drying and used the page model for drying characteristics.

Ghazanfari et al., (2003) developed a forced convection direct solar dryer and tested for the drying of pistachio nuts. The moisture content of the nuts was reduced from 40% to 6% (wb) after 36 hours of drying.

Singh et al., (2004) developed a multi-shelf portable solar dryer that can be used as both direct type and indirect type of dryer depending upon the requirements as there is an arrangement of shading plates. The maximum stagnation temperature inside the dryer and the average overall heat loss coefficient at no load condition were found to be 75 °C and 12 W/m^2 K, respectively. Thermal efficiency of the dryer for fenugreek drying was in the range of 8.6% to 28.55% and 25.3% to 28.96% for batch and semi-continuous mode, respectively.

Singh et al., (2006) designed and developed a natural convection direct type domestic solar dryer and experimented under no-load and load conditions. The thermal efficiency of the dryer ranged from 5.16% to 28.05% and 19.3% to 25.6% for batch mode and semi-continuous mode, respectively. The payback time was observed to be 204 and 86 drying days for drying fenugreek

leaves and chili drying, respectively. The drying cost was reduced by 40% as that of an electric dryer.

Al-Juamily et al., (2007) used two solar air collectors with V-corrugated absorption plates in a multi-shelf mixed mode solar dryer. The moisture content of beans, apricots and grapes was reduced from 65 to 18%, 80 to 13%, and 80 to 18% in one, one and a half, and two and a half days, respectively.

Gbaha et al., (2007) used a direct solar dryer for drying cassava, bananas and mango. The global heat loss factor was observed to be 5.262 W/m^2 °C. The average drying effectiveness was found to be 13.65%.

Hassanain (2009) compared the performance of a mixed mode solar dryer with horizontal and vertical drying chambers under active and passive mode for the drying of banana. The system with a horizontal drying chamber shows faster drying with a higher value of drying constant for banana drying.

Sengar et al., (2009) fabricated a low cost solar dryer of size 92 cm × 75 cm having 16 trays of dimensions of 70 cm × 50 cm with a total capacity of 10 kg of prawns. The average drying efficiency was 11% and 14% for simple and salted prawns drying. The payback period was less than 3 months for a total cost of INR 1700.

Rawat et al., (2009) performed an energy analysis on a direct type solar crop dryer for chili drying under natural convection. The moisture content was reduced from 74.4% to 4.4% (wb) in 8 hr. Total energy embodied in the dryer during the life was observed to be 2744.64 MJ. The lifetime of the dryer was estimated to be 10 years with an energy payback period of 1.10, 1.32, 1.55 and 1.77 years in terms of fuel-wood, coal, light diesel oil and natural gas, respectively.

Saleh and Badran (2009) tested a soalr dryer under no-load condition and then under load condition for the drying of Jew's mallow and mint leaves in fixed and tracking mode. The values of stagnation temperature and the average heat loss coefficient were found to be 80 °C and 9.6 W/m^2 K, respectively. The average thermal efficiency for Jew's mallow leaves drying was observed to be 3.74% and 7.08% under the fixed and tracking mode, respectively.

Amanlou and Zomorodian (2010) applied computational fluid dynamics for the evaluation of temperature and air-flow distribution inside a conventional cabinet dryer with 7 different design modifications. The value of the coefficient of correlation was found to be 99.9% and 86.5% for the temperature and flow velocity of the drying air.

Afriyie et al., (2011) studied the effect of inclination of the roof of the drying chamber and the height of the chimney on the airflow rate throughout the system. The chimney was made up of transparent material except for the back that has a heat-absorbing surface for heating the air. It was observed that an inlet-exit ratio of 4:1 should be used for maximum ventilation.

Bolaji et al., (2011) compared the performance of a mixed-mode solar dryer having rotary wind ventilator and a simple natural convection mixed-mode dryer for the drying of pepper and yam chips. The average efficiency of the dryer with and without a ventilator was recorded to be 46.7% and 31.2%.

Dissa et al., (2011) studied the drying characteristics of the two verities of mangoes (Amelie and Brooks) in direct solar drying. The drying efficiency was found to be in the range of 0-34.13% throughout the drying period.

Wakjira et al., (2011) developed an enclosed solar dryer and tested for the optimum slice thickness for the drying of banana slices in the climate conditions of Ethiopia. They suggested that a slice thickness of 3-4 mm must be used for getting a top quality product. The dryer took 4 days to dry the product.

Berinyuy et al., (2012) used a natural convection solar dryer with a chimney and a solar air heater having an arrangement for energy storage. It was observed that the energy storage could maintain a 5 °C higher temperature than the ambient temperature at the end of the day. The overall efficiency of the dryer was found to be 17.68%, with a payback period of 18 months.

Eltawil et al., (2012) developed a mixed mode solar cabinet dryer with a chimney having wind-powered suction fan. It was observed that the dryer could dry the potato chips and peppermint in a single clear sunny day as it took 9-10 and 5-6 hours for the drying of respective commodities.

Seveda and Jhajharia (2012) developed and tested a direct cabinet type solar dryer under forced convection mode to dry large cardamom (Amomum Subulatum). The moisture content was

reduced from 75.6% (wb) to 10.1% (wb) in a drying time of 24 hours, whereas it took 48 hours for the same in case of open sun drying.

Singh and Kumar (2012) in research proposed a dimensionless parameter named 'no-load performance index' (NLPI) for the evaluation and comparison of the performance of the various solar dryer. It was observed that the NLPI for a solar dryer working under a given air flow condition is more or less independent of absorbed thermal energy and ambient air temperature data (climatic variables).

Singh and Kumar (2012a) tested a mixed mode forced convection solar dryer in different conditions to develop a new performance indicator 'dryer performance index' (DPI) for a solar drying system. The proposed model was observed to independent of claimat conditions and food properties.

Eke (2013) compared the performance of a natural convection direct type solar dryer having a solar collector with different absorbing materials (metal, wood, cement and mud). The drying time and the drying efficiency were observed to be 222 h, 96 h, 96 h, 94 h, and 76 h; and 7.38%, 19.56%, 20.25%, 20.91% and 27. 24%, for open sun, wood, cement, mud, and metal solar collector, respectively. At the same time, the production cost was 15000, 10470, 8860, and 5000 for a dryer with metal, cement, wood and mud as absorbing materials.

Elkhadraoui et al., (2015) investigated a mixed mode forced convection chapel-shaped solar greenhouse dryer with a flat plate solar collector to dry red pepper and sultana grape. It was observed that the moisture content of red pepper and Sultana grape was reduced to 16% (wb) and 18% (wb) in 17 hours and 50 hours by using a greenhouse dryer, whereas in the open sun drying it takes 24 hours and 76 hours, respectively.

Navale et al., (2015) designed and developed a direct type cabinet solar dryer and tested for the drying of fenugreek leaves. A chimney with a black painted interior and transparent front was provided for improving the natural convection. The average drying efficiency was found to be 34.50%, which was much higher than open sun drying.

Terres et al., (2015) developed a direct type of natural convection solar dryer having two separate transparent glass covers and 5 trays for the drying of lemon slices. A reduction of 50% in

the mass of the product was observed in a drying time of 10 hours. They used ANSYS software to simulate the drying chamber for temperature, density and airflow currents.

Prakash et al., (2016) modified a greenhouse dryer by using thermal energy storage and various floor conditions. The black PVC floor was observed to be the most effective, among others. The coefficient of performance and exergy efficiency ranges from 0.55 to 0.87 and 0.58–0.73; and 29% to 86% and 30% to 78% for natural and forced convection, respectively.

Sonthikun et al., (2016) designed a solar-biomass hybrid dryer for rubber sheets drying. Direct solar radiation was used to heat up the inside air in the day time and a biomass burner was used to maintain the inside temperature at night time. The dryer took 48 h to reduce the moisture content from 34.26% to 0.34% (db). The value of R^2 ranges from 0.96 to 0.99, showing a strong agreement in the results of experimental and CFD analysis.

Jangsawang (2017) developed a solar cabinet dryer of size 1.2×1.2×1.2 m attached with a greenhouse chamber at the top separated by a black absorbing aluminum sheet having the arrangement to force the heated from the head to the drying chamber. A temperature variation of 1 to 3 ℃ was observed among the 5 drying trays with a maximum temperature of 48.63℃. A higher percentage of weight loss was recorded with the solar dryer as compared to open sun drying.

Modi et al., (2017) fabricated a direct type of cabinet dryer and used for the drying of tomato slices under forced convection mode. The moisture content was reduced from 90.48% (wb) to 7.73% (wb) with an overall dryer efficiency of 34.87%.

Poonia et al., (2017) developed a low-cost direct type solar dryer and tested the same for the drying of Ziziphus (ber). A maximum stagnation temperature of 60°C was observed. The dryer took 6 days to reduce the moisture content from 85% to 15% (wb) with an overall efficiency of about 16% and the total cost of INR 800.

Castillo Téllez et al., (2018) used a cabinet type direct solar dryer under free and forced convection and drying kinetics of stevia leaves. The highest drying rate was observed to be 0.0554 kg water/kg dry matter in free convection direct solar dryer without shading for initial moisture content of 3.237 to 0.1405 kg water/kg dry matter.

Chaudhari et al., (2018) used a direct type natural convection cabinet with an electric heating system in the bottom of the cabinet for ginger drying. The dryer took 9 hours to reduce the moisture content from 79.31% (wb) to 6.73% (wb), whereas the reduction was just up to 66.38% (wb) in open sun drying. The payback period was estimated to be 6 months, with an estimated lifetime of 3000 working days.

Fterich et al., (2018) experimented on a forced convection mixed-mode solar dryer having a photovoltaic-thermal collector at the top. The tomato slices were dried from a moisture content of 91.94% (wb) to 22.32% (wb) with a significantly reduced drying time and improved product quality in comparison to the open sun drying.

Jain et al., (2018) conducted a study on the computational fluid dynamic analysis of a direct type of domestic solar dryer under natural convection mode. The convective heat transfer coefficient was observed to be 2.81 W/m^2 °C with a significant temperature of 55°C around the tray, coefficient of performance of 0.46 and heat utilization factor of 0.69. The reliability of the results was observed in terms of the coefficient of determination (R^2), which was found to be 0.98.

Sandali et al., (2018) investigated the effect of porous medium as sensible heat storage in a direct type of solar dryer. The drying temperature was increased by 4 °C and the working time of the dryer was extended by 2 hours after sunset with the proposed modification. They suggested that the thickness of the porous medium can be increased for higher temperatures.

Alonge and Obayopo (2019) designed a direct type of solar fish dryer and tested the same numerically and experimentally for optimum dimensions at various airflow rates under no-load and loaded conditions. Maximum temperature and collection efficiency were observed in natural convection mode i.e., at a fan speed of 0 m/s.

Aydin et al., (2019) developed and tested a mixed-mode modular solar dryer. Two modular drying chambers with two different drying trays were used for maximum output. The average drying efficiency for apple, banana, chili, and grapes was found to be 38.01%, 43.84%, 40.03%, and 42.13%, respectively.

Djebli et al., (2019) studied a mixed-mode solar greenhouse dryer. Tomato samples were prepared by cutting in the form of flat slices (thickness 0.5, 1, 1.5, and 2 cm) and wedges (2, 4, 8

and 16 sections). The dryer took 5 to 21.25 hours for flat slices and 8.5 to 28.25 hours for the wedges to reduce the moisture up to the required range of 18 to 25% (db).

Islam et al., (2019) constructed a direct type of solar dryer with three separate drying chambers having different arrangements for ventilation (a thin tube chimney type, attic type, and simple type). Simple natural convection type drying chamber was found to be the most efficient with a maximum moisture removal rate of 58.9% as compared to 44.5% for chimney type and 33.3% for attic type ventilated drying chamber.

Lakshmi et al., (2019) developed a new mixed-mode forced convection solar dryer and tested for the drying of stevia leaves. The overall efficiency of the dryer was observed to be 33.5%, with a reduction of 62% in the drying time as compared to open sun drying and a payback period of 7.8 months.

Mohsen et al., (2019) fabricated a simple direct type solar dryer and tested the same for the drying of tomato. They compared the performance of the dryer with open sun drying with different thicknesses (1, 1.5, and 2 cm) of the tomato slices and increasing the number of layers (single, double, triple) of the tomato. A maximum decrease of 56% in the drying time was observed in the case of single-layer drying with 1 cm thickness of the product.

Ekka and Palanisamy (2020) evaluated the heat transfer coefficients for forced convection mixed-mode solar dryer with a thermal energy storage system. Paraffin wax was used as a phase change material for thermal storage. The average convective and evaporative heat transfer coefficients were 1.63 and 49.7 W/m^2 °C, respectively. A reduction of 50% was observed in the drying time with the use of thermal storage.

Ekka et al., (2020) analyzed the effect of using two successive air flow rates in forced convection mixed-mode solar dryer. Initially, the air-flow rate was 0.062 kg/s, and then 0.018 kg/s as the drying rate starts falling. The moisture content was reduced from 75% (wb) to 3.3% (wb) with a higher drying efficiency of about 4.4% as compared to constant airflow rate drying. A significant reduction in the drying time and specific energy consumption was also observed.

Mohammed et al., (2020) fabricated an improved hybrid solar dryer and tested for the drying of pineapple under free and forced convection mode. The dryer took 18 hours to dry the

product, whereas it needs 30 hours in case of open sun drying. The payback period was estimated to be 9.6 months.

Ndukwu et al., (2020) analyzed the performances of a mixed-mode solar dryer under natural and forced convection with and without glycerol as thermal storage. Higher drying efficiency was observed in active mode with thermal storage however the total useful energy consumption and energy produced by thermal storage were higher in the case of passive mode.

Sandali et al., (2020) analyzed the effect of various techniques of heat supply (heat exchange, porous medium and PCM) on a direct solar dryer. The payback period was found to be in the range of 0.8 years to 5.4 years, with an expected lifetime of 15 years for various arrangements.

Silva et al., (2020) developed a hybrid solar dryer by using a photovoltaic panel for supplying power to the fans and electric heater and preheating of air before entering into the solar collector. The moisture content of the corn was reduced from 23% to 13% in 8 hours, whereas it takes 24 hours in open sun drying.

Phase change materials are being studied for drying applications. Some studies on solar drying systems with phase change materials as energy storage are summerised in table 1.

Many researchers had reviewed the solar drying systems and suggested for possible improvements. Various reviews and recommendations on solar drying are given in table 2.

Table 1 Summary of studies on solar drying with phase change material.

S. No.	Researcher/s (Year)	PCM used	Remarks
1	Shalaby and Bek (2014)	Paraffin wax	A favorable drying temperature was observed for about 7 hr after sunset for the drying of Ocimum Basilicum and Thevetia Neriifolia in an indirect dryer.
2	Jain and Tiwari (2015)	Paraffin wax	The temperature inside the drying chamber was higher than the ambient temperature throughout the night. The thermal efficiency and the payback period of the dryer were 28.2%and 1.5 years, respectively.
3	Sreerag and Jithish (2016)	Paraffin wax and Glauber's salt	The drying rates for the dryer with and without the PCM were 0.055 kg/hr and 0.047 kg/hr for the drying of green banana.
4	Lakshmi et al., (2017)	Paraffin wax	The drying time for black turmeric drying in a mixed-mode dryer was observed to reduce by 60.7% as compared to open sun drying. The overall efficiency of the system was 12%.
5	Baniasadi et al., (2017)	Paraffin wax	A maximum drying rate of 2.1 g/hr was observed before noon. A reduction of 50% was recorded in the drying time of apricot by using PCM in a mixed-mode solar dryer.
6	Krishnan and Sivaraman (2017)	Mixture of paraffin and kerosene in a ratio of 2:1	The thermal efficiency of the solar cabinet dryer was improved by 50% with the use of PCM.
7	Kaewpanha et al., (2018)	Paraffin wax	A 16.72 °C higher temperature than the ambient was maintained inside the drying chamber of an indirect solar dryer after sunset for about 3 hours.

8	Swami et al., (2018)	Paraffin wax	The drying time was reduced by 80% with the use of PCM in an indirect solar dryer as compared to traditional fish drying.
9	Khouya and Draoui (2019)	RT64 (Paraffin), RT82 (Paraffin) and Erythritol (Alcoholic sugar)	The drying efficiency was observed to be 85% with a reduction of 26.5% in drying time for wood drying in a solar kiln.
10	Azaizia et al., (2020)	Paraffin wax	The drying time of red pepper in the greenhouse with PCM was found to be 30 hours, whereas it took 55 hours without PCM and 75 hours in open sun drying.

Table 2 Summary of reviews on solar drying.

S. No.	Researcher/s (Year)	Study	Remark
1	Sharma et al., (2009)	Solar-energy drying systems: A review	Presented a detailed review of various available solar drying technologies. Easy-to-fabricate and operate low-cost drying techniques were recommended for small agro-industries, villages, farms, and domestic applications.
2	Bal et al., (2010)	Solar dryer with thermal energy storage systems for drying agricultural food products: A review	Suggested that the investigations must be done on energy storage systems for their performance improvements in heat storage and transfer capacities. PCM other than paraffin wax must be researched and used for various drying applications.
3	Fudholi et al., (2010)	Review of solar dryers for agricultural and marine products	Various solar dryers for agricultural and marine products were reviewed with their technical and economic aspects. A need for better heat transfer and storage system was highlighted in conclusion.
4	Belessiotis and Delyannis (2011)	Solar drying	Presented various phenomena involved in the drying process and also the literature related to solar drying.
5	El-Sebaii and Shalaby (2012)	Solar drying of agricultural products: A review	Concluded that investigations must be done on the compatibility and durability of PCM in a different solar dryer. Computer simulation must be done for design and optimization. The study was more focused on the literature of indirect drying and solar air heating systems.

6	VijayaVenkataRaman et al., (2012)	A review of solar drying technologies	Reviewed various solar drying techniques for different commodities in developing nations. The technologies for extending the working hours during the off-shine period were also discussed.
7	Kumar et al., (2014)	Review on global solar drying status	Reviewed the recent studies on direct, indirect and mixed-mode type natural and forced convection solar dryers for some specific drying commodities with their design and performance details.
8	Mustayen et al., (2014)	Performance study of different solar dryers: A review	Studied the various available designs of different types (direct, indirect, and mixed type) of solar dryer. They concluded that an efficient dryer is that which reduces the drying time, maintains the quality of the produces, and at the same time needs lower investments and simple in construction and use.
9	Pirasteh et al., (2014)	A review on development of solar drying applications	The role of the solar drying technique in agriculture and industrial applications has been reviewed. It was suggested that detailed investigation must be performed for the empowerment of solar drying technologies in industrial applications.
10	Chauhan et al., (2015)	Applications of software in solar drying systems: A review	Reviewed the software available for the simulation of different solar drying systems. It was concluded that ANSYS, FLUENT, TRNSYS, Comsol Multiphysics, and MATLAB are the most widely used simulation tools for the design and optimization of various solar dryers. Sigma Plot V, SPSS and Statistica are also used for various statistical analyses.

11	Kumar et al., (2016)	Progress in solar dryers for drying various commodities	Reviewed the three types (direct, indirect, and hybrid types) of a solar dryer for drying different products in the developing countries.
12	Sahdev et al., (2016)	A review on applications of greenhouse drying and its performance	Presented a review on various designs and modifications of greenhouse dryers for different drying commodities. They proposed that further research should be dome on hybrid sustainable dryers.
13	Kiggundu et al., (2016)	Solar fruit drying technologies for smallholder farmers in Uganda, A review of design constraints and solutions	Concluded that the researchers should draw a thin line between the costs and benefits of materials used for the fabrication of solar dryers. Simulation studies must be done to optimize the system for various climate conditions. The modification must assure a visible improvement in the capacity of the system, quality of the dried product, and ease in operation, construction and maintenance.
14	Mall and Singh (2017)	Advanced technologies and experimental investigations in solar dryers: A review	It was reported that the hybrid dryer with latent heat storage is the best for rural applications in terms of better efficiency and lower drying time.
15	Prakash et al., (2017)	Applications of soft computing in solar drying systems	Presented a comprehensive review of various software used in optimizing the solar drying processes. COMSOL Multiphysics, TRNSYS, MATLAB, FORTRAN, CFD Fluent were some widely used software tools for solar drying.
16	El Hage et al., (2018)	An investigation on solar drying: A review with	In a detailed investigation of solar drying systems concluded that the economic and environmental analysis must be done for solar technologies with thermal and energy analysis. Efforts were

		economic and environmental assessment	recommended for the awareness, promotion and publicity of solar drying technologies.
17	Mofijur et al., (2019)	Phase change materials (PCM) for solar energy usages and storage: An overview	Reviewed the applications of PCM in different solar technologies such as solar power generation, water heating systems, solar cookers, and dryers. They concluded that PCM with high efficiency, low cost and longer life must be investigated and used for solar technologies.
18	Chavan et al., (2020)	Natural convection and direct type (NCDT) solar dryers: a review	Various studies on direct type free convection solar drying systems were reviewed. The drying time, drying rate, simple design, cost, compactness and portability were the most focused parameters for these dryers.
19	Mohana et al., (2020)	Solar dryers for food applications: Concepts, designs, and recent advances	Reviewed the studies on the design, development and improvement of various types of solar dryers for different commodities conducted in the past five years. They suggested that present phase change materials must be investigated in detail with simultaneous research on some new PCM.
20	Ndukwu et al., (2020)	Solar drying research of medicinal and aromatic plants: An African experience with assessment of the economic and environmental impact.	Reviewed various studies on solar drying of medicinal and aromatic plants in the region of Africa. Drying kinetics was found to be the most focused element of most researches, while economic and environmental aspects were studied less. Equal importance must be given to every aspect of analysis or different analyses for better understanding and detailed conclusions.

3. Literature gap

The lack of proper storage facilities and preservation techniques results in a significant wastage of food items at households and small agriculture farms, specially in rural or remote areas where electric supply is either not available or costs too high. Typically refrigerators were used for storing fruits and vegetables. That requires continuous electric supply and with that the commodities can't be stored for more than a week. The present study is an effort to reduce the wastage of food items and eliminate the requirements of electricity by introducing a domestic hybrid solar dryer. That can be used to dry various commodities such as fruits, vegetables, and crops available in excess at housdeholds and small agriculture farms. The product, after drying has no power requirements and can be stored for about more than a whole year.

Various researches have been done on solar dryers as there is always a question of lower performances and limited daytime use on these solar drying technologies. It is observed from the literature that maximum studies are focused on the performance enhancement of the dryer that makes the overall system more complex in terms of construction, use, maintenance and the total cost of the system increases as well. The present study has been designed to address the same question by designing, fabricating and testing a domestic hybrid solar dryer. The phase change material interior will be used for energy storage during the day time so that this stored energy can be used in off-shine periods. Photovoltaic panel will be used for the power requirement in case of forced convection drying. All the experimental investigation will be performed in the climate conditions of Hisar for various analyses.

4. Problem formulation

Solar dryers need solar energy for functioning, and in this way, it eliminates the requirements of electricity. A domestic hybrid solar dryer will be designed, fabricated, and tested with simulation and experimental analyses. The dryer will be entirely solar-powered with a thermal energy storing interior and a photovoltaic panel arrangement for forced convection drying operations.

5. Objectives

The proposed study will be evaluated on the achievement of the following objectives:

- Design and simulation of a domestic hybrid solar dryer.
- Optimization of different design and operating parameters of domestic hybrid solar dryer.
- Fabrication of domestic hybrid solar dryer.
- Experimentation for temperature stagnation, unload and load conditions.
- Drying kinetics for some agricultural produce using domestic hybrid solar dryer.
- Thermodynamic performance analysis based on observed parameters during experimentation.
- Embodied energy analysis of developed solar drying systems.

6. Proposed methodology

The designing, simulation, and optimization of the domestic hybrid solar dryer will be done using computer software. Fabrication of the domestic hybrid solar dryer will be performed to investigate the proposed design experimentally. The experimental data will be used for drying kinetics, thermodynamic, and embodied energy analyses. The following governing equations will be used for various calculations.

Thermodynamic analysis

Thermal modeling

The heat balance equation for the inside air temperature may be written as (Sodha et al., 1985).

Heat absorbed by air inside the cabinet = Heat used to raise the temperature of air + Energy gained by the product from inside air + Energy used in moisture evaporation

$$(\alpha_p \tau_g) I = m c_{pa} \frac{\delta t}{\delta x} + h_a (T_a - T_p) + \rho_p h_{fg} \frac{\delta m}{\delta t} \quad (1)$$

The heat balance equation for the drying commodity may be written as (Sodha et al., 1985).

Direct heat absorbed by the commodity + Energy gained by the commodity from inside air = Energy utilized to increase the temperature of the commodity

$$(\alpha_p \tau_g) I + h_a (T_a - T_p) = h_a (\rho_p c_{pp} - \rho_p c_{vp} m) \frac{\delta T_p}{\delta t} \quad (2)$$

Where,

α_p Absorptivity of the product

τ_g Transmitivity of the glass

I Solar radiation intensity, W/m^2

h_a Convective heat transfer coefficient, W/m^2 ℃

T_a Temperature of inside air, ℃

T_p Temperature of the product, ℃

c_{pa} Specific heat for air, J/kgK

ρ_p Density of the product, kg/m^3

Convective and evaporative heat transfer coefficients

For evaluating the values of convective heat transfer coefficient (Tiwari et al., 2006; Kumar et al., 2011; Prakash and Kumar, 2014).

$$h_c = \frac{K_v}{X}\, C(Gr\ Pr)^n \qquad (For\ natural\ convection\ mode) \qquad (3)$$

$$h_c = \frac{K_v}{X}\, C(Re\ Pr)^n \qquad (For\ forced\ convection\ mode) \qquad (4)$$

Where,

h_c Convective heat transfer coefficient, W/m^2 ℃

K_v Thermal conductivity of humid air, W/m ℃

C Experimental constant

Gr Grashof number

Pr Prandtl number

n Experimental constant

Re Reynolds number

For evaluating the values of evaporative heat transfer coefficient (Jain et al., 2010; Kumar et al., 2019).

$$h_e = \frac{Q_e}{T_P - T_e} \quad (5)$$

Where,

h_e Evaporative heat transfer coefficient, W/m^2 ℃

Q_e Rate of heat used to evaporate moisture, J/m^2 s

T_P Temperature of the product surface, ℃

T_e Temperature just above the product surface, ℃

Thermal efficiency of the dryer

The thermal efficiency (η_{th}) of the dryer is the ratio of the energy which is used to evaporate the moisture from the product to the energy supplied to the dryer through the solar radiations which can be evaluated as (Ayyappan et al., 2015).

$$\eta_{th} = \frac{m_{ev}\lambda}{IA_g t} \quad (6)$$

Where,

m_{ev} Moisture evaporated, kg

λ Latent heat of vaporization, J/kg

I Solar radiations, W/m^2

A_g Area of the glass, m^2

T Time, s

Analysis of drying characteristics

The moisture content of the samples on a wet basis (M_{wb}) and moisture ratio (MR) were determined by the following equations (Kesavan et al., 2019).

$$M_{wb} = \frac{m_i - m_f}{m_i} \quad (7)$$

$$MR = \frac{(M_t - M_e)}{(M_i - M_e)} \quad (8)$$

Where,

m_f Final mass of the product, g

m_i Initial mass of the product, g

M_t Moisture content at 't' drying time, % (wb)

M_e Equilibrium moisture content

M_i initial moisture content, % (wb)

M_e is considered negligible when compared to M_t and M_i for a long drying time. Therefore, the equation can be simplified as:

$$MR = \frac{M_t}{M_i} \tag{8}$$

The drying rate (DR) was expressed as the amount of moisture evaporated over time and is evaluated as (Arun et al., 2019).

$$DR = \frac{(M_{t+dt} - M_t)}{dt} \tag{9}$$

For drying model selection, drying curves have been fitted to thin-layer drying models. The best of fit has been determined using three parameters: higher values for the coefficient of determination (R^2), least values for reduced chi square (χ^2) and root mean square error (RMSE) as (Vijayan et al., 2016).

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(\overleftarrow{MR} - MR_{pre,i}\right)^2}\right] \tag{10}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - x} \tag{11}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \tag{12}$$

Where,

$\overleftarrow{MR}$ Mean dimensionless moisture content

$MR_{exp,i}$ Experimentally predicted moisture ratio

$MR_{pre,i}$ Predicted moisture ratio

N Number of observations

x Number of a model's constants

Embodied energy analysis

Energy payback time

The Energy payback time (EPBT) is used to estimate the total period required to redeem the energy spent for the fabrication of the solar dryer and its components, and the value depends on the materials used. It is the ratio between the total embodied energy and the annual energy output from the system (Kesavan et al., 2019).

$$EPBT = \frac{\text{Total Embodied Energy}}{\text{Annual Energy Output}} \quad (13)$$

The annual energy output of the solar dryer can be found using the following equation.

Annual energy output = Daily energy output × Number of days

Where,

$$\text{Daily energy output} = \frac{W \times L}{3600}$$

W Total mass of water removed, kg

L Latent heat of water, kJ/kg

CO_2 emission

The CO_2 emission per year can be calculated as (Prakash et al., 2016).

$$CO_2 \, emissions \, per \, year = \frac{\text{Embodied Energy} \times 0.98}{\text{Lifetime}} \quad (14)$$

7. Proposed research plan

The proposed research plan for the study is as follows:

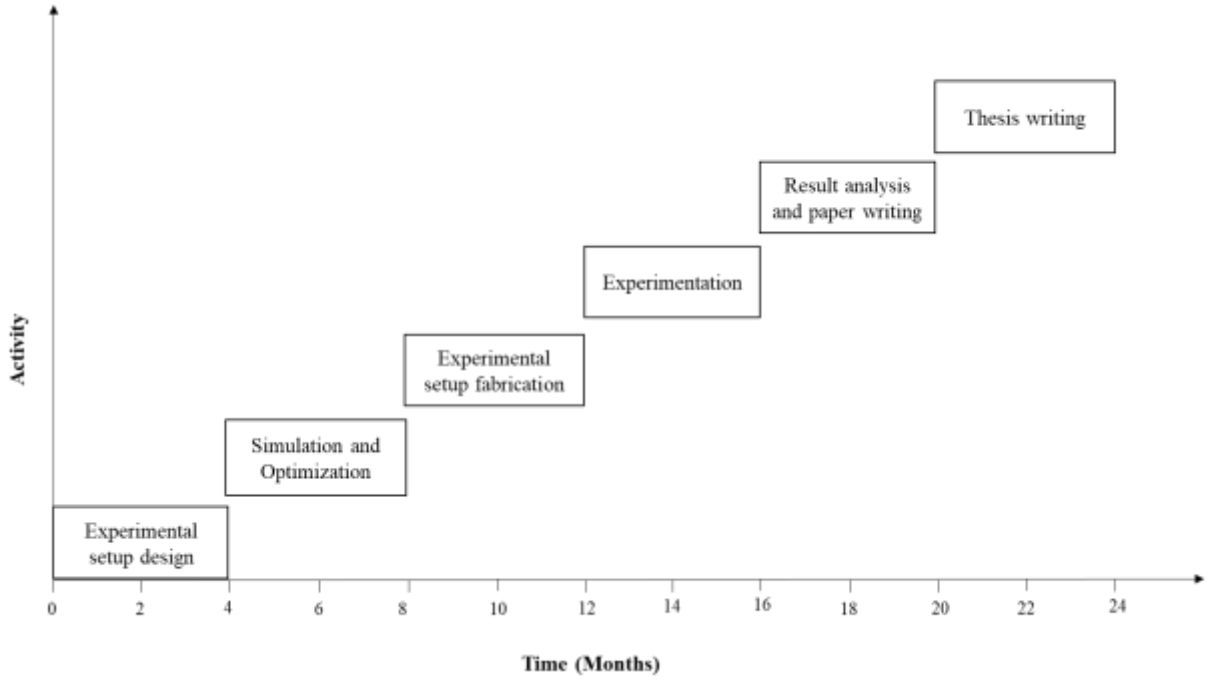

Figure 7 Proposed research plan

8. Proposed research outcomes

The expected outcomes from the proposed research are given as:

- Energy-efficient and environmentally sustainable domestic hybrid solar dryer will be developed from the proposed work.
- Two SCI publications in peer-reviewed journals are also expected as an outcome from the proposed work.

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